13A.2 ASSIMILATION OF WIND PROFILES FROM MULTIPLE DOPPLER RADAR WIND PROFILERS FOR SPACE LAUNCH VEHICLE APPLICATIONS.

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1. INTRODUCTION

Space launch vehicles utilize atmospheric winds in design of the vehicle and during day-of-launch (DOL) operations to assess affects of wind loading on the vehicle and to optimize vehicle performance during ascent. The launch ranges at NASA's Kennedy Space Center co-located with the United States Air Force's (USAF) Eastern Range (ER) at Cape Canaveral Air Force Station and USAF's Western Range (WR) at Vandenberg Air Force Base have extensive networks of in-situ and remote sensing instrumentation to measure atmospheric winds. Each instrument's technique to measure winds has advantages and disadvantages in regards to use for vehicle engineering assessments. Balloons measure wind at all altitudes necessary for vehicle assessments, but two primary disadvantages exist when applying balloon output on DOL. First, balloons need approximately one hour to reach required altitude. For vehicle assessments this occurs at 60 kft (18.3 km). Second, balloons are steered by atmospheric winds down range of the launch site that could significantly differ from those winds along the vehicle ascent trajectory. Figure 1 illustrates the spatial separation of balloon measurements from the surface up to ~55 kft (16.8 km) during the Space Shuttle launch on 10 December 2006. The balloon issues are mitigated by use of vertically pointing Doppler Radar Wind Profilers (DRWPs). However, multiple DRWP instruments are required to provide wind data up to 60 kft (18.3 km) for vehicle trajectory assessments. The various DRWP systems have different operating configurations resulting in different temporal and spatial sampling intervals. Therefore, software was developed to combine data from both DRWP-generated profiles into a single profile for use in vehicle trajectory analyses. Details on how data from various wind measurement systems are combined and sample output will be presented in the following sections.

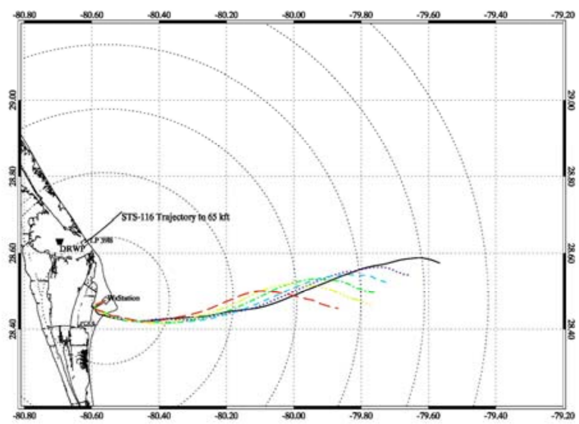

Figure 1. Spatial separation of balloons during Space Shuttle launch at the ER Launch Complex 39B on 10 December 2006. Six balloons were released over 6-hr period prior to launch represented by different colored lines. Black dot circles are 10 nmi range rings away from the ER balloon release facility.

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2. DESCRIPTION OF RANGE INSTRUMENTATION

Atmospheric wind measurements at the ranges can be made from a variety of instrumentation systems. Directly measured winds are made with a balloon-lofted instrumented package that transmits data back to a ground-based receiving system known as the Automated Meteorological Profiling System (AMPS) (Divers et al. 2000). The AMPS has the capability of using different balloons to loft its instrument package. The Low-Resolution Flight Element (LRFE) uses a standard latex balloon that has a rise rate of 1000 ft/min (5.1 m/s) and reaches ~100 kft (30.5 km) before the balloon bursts. The AMPS instrumented package can also be lofted on a specially designed balloon, known as a Jimsphere, to make high-resolution wind measurements (Wilfong et al. 1997, Adelfang 2003, Wilfong et al. 2000). The balloon itself is more rigid than a latex balloon plus it contains roughness elements to reduce self-induced oscillation during ascent (Wilfong et al. 1997). The Jimsphere also contains a vent valve in order to maintain a constant volume as the balloon ascends. However, maintaining constant volume limits the altitude range the balloon can achieve. A Jimsphere can typically reach between 55-60 kft (16.7-18.3 km) (Wilfong et al. 1997).

Wind measurements can also be obtained from ground-based remote sensing instruments. Vertically pointing DRWP systems are ground-based instruments that transmit and receive electronic pulses that can be converted to wind velocity and direction. The DRWP transmitted frequency and antenna size dictates the altitude range sampled and the sampling interval. Since the mid-1990s, the ER and WR have had multiple frequency DRWPs to sample different atmospheric regimes. A 50-MHz DRWP is used to sample the free troposphere from 6 – 60 kft (2.0-18.3 km) and multiple 915-MHz DRWPs are used to sample the atmospheric boundary layer from 0.6-10 kft (0.2-3.0 km). Unlike balloon-based systems, the DRWP systems operate continuously, with the 50-MHz DRWP reporting measurements approximately every 5-mins and the 915-MHz DRWP reporting measurements approximately every 15-mins.

3. WIND MEASUREMENT DATA FOR LAUNCH VEHICLE ASSESSMENTS

Space launch vehicles respond to low and high frequency wind perturbations with wavelengths ranging between tens of meters up to thousands of meters. These wind characteristics need to be accounted for in design studies to establish vehicle structural integrity and ascent performance. It is also important to quantify atmospheric temporal wind change to protect for wind uncertainties in DOL commit-to-launch decisions. Therefore, it is necessary to obtain atmospheric wind measurements that capture high- and low-resolution wavelengths and temporal wind change over multiple atmospheric seasons in order to develop a statistically representative sampling of the wind environment for robust engineering analyses.

Historically, space launch vehicle engineering assessments have used atmospheric wind measurements solely from data collected by high- and low-resolution balloon measurements. While low-resolution balloon measurements are routinely made to support range weather observing and forecast model input, they lack high frequency wind content. Conversely, high-resolution balloon measurements are only used to support launch operations where frequent balloon measurement are performed to quantify temporal wind change and the wind affects on vehicle loads and trajectory. These factors result in insufficient wind data archives necessary for robust engineering assessments.

Several limitations exist with the balloon systems when using to support DOL operations. First, balloons require approximately one hour to reach required altitudes. Second, balloons are steered by atmospheric winds down range of the launch site that could significantly differ from those winds along the vehicle ascent trajectory in the time necessary for the balloon to reach altitude. The acquisition and installation of DRWP systems at the ER and WR was predicated to overcome/mitigate the shortcomings of the balloon systems. Programmatic decisions by NASA's Space Shuttle Program resulted in neither range DRWP system becoming certified for use in DOL trajectory and loads evaluations. As NASA is developing the Space Launch System (SLS) vehicle there is an effort underway to design, verify and operate the vehicle to take advantage of the various wind measurement systems. This approach minimizes the limitations that exist between several wind observation systems. However, in order to use wind data from DRWP instruments in vehicle trajectory assessments, multiple DRWP instruments are required to provide wind data over required altitude ranges. The following sections present details on how data

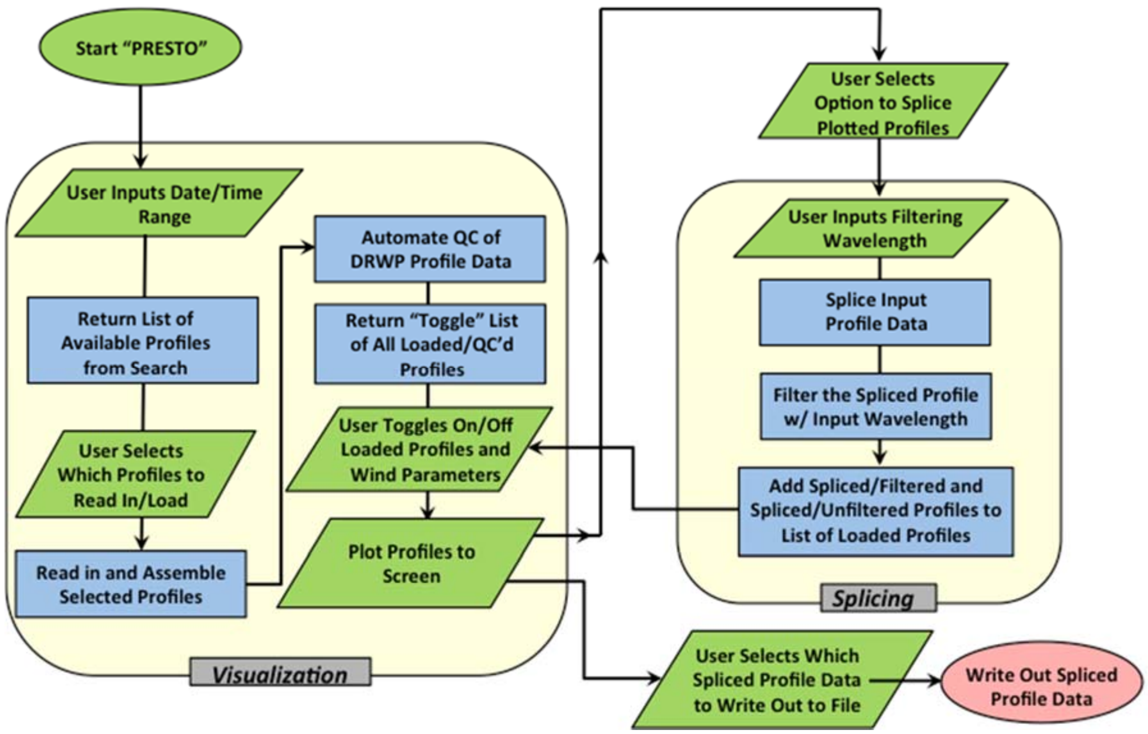


Figure 2. Flow Diagram of PrESTo.

from various wind measurement systems are combined.

4. DATA VISUALIZATION AND PROFILE SPLICING

The Profile Envision and Splice Tool (PrESTo) is a software package that, through a graphic user interface (GUI), allows the user to visualize wind (and thermodynamic) profiles from multiple sources and splice profiles together based on user selections. PrESTo is intended for use during DOL operations in the support of spacecraft launches. It will enable users to visualize incoming data from all available measurement systems and to create a vertically complete profile of a given variable. These variables include wind speed, wind direction, wind components, temperature, pressure, and density.

Marshall Space Flight Center's Natural Environments Branch has developed PrESTo using Python, which provides advantages over writing analogous software in a comparable, proprietary language. Python maximizes portability as PrESTo will be able to run on multiple operating systems (Unix, Mac OS and Windows). PrESTo currently utilizes three Python modules: NumPy, which handles some of the more advanced mathematical calculations; XLRD, which allows for reading data from an Excel file of upper air climatologies; and Matplotlib, which produces graphs of the profiles.

PrESTo enables users to visualize and splice data from multiple instruments within a specified date and time range, and to write spliced profiles to a file for use in DOL trajectory and loads assessments. Figure 2 provides a flow diagram of PrESTo's inputs and outputs. First, the software returns a list of all profiles recorded during a specified date and time range. From this list, the user selects which profiles to visualize. Once these profiles are selected, PrESTo implements a quality control process on any selected data from the 50- or 915-MHz DRWP closely following Barbré (2015). PrESTo then generates a separate window that contains the profiles one desires to visualize, which include the checked DRWP data. This window also provides the ability to plot the wind speed, wind direction, u and v wind components, temperature, dew point, and density. In addition, this window contains an option to splice profiles together. The splice command uses either a user defined filter wavelength or an unfiltered, default calculation. After generating the spliced profile, PrESTo overlays the spliced profile with the previously selected profiles to visually compare the spliced profile to the profiles used to build it. Finally, an option exists to write the spliced profile to text file.

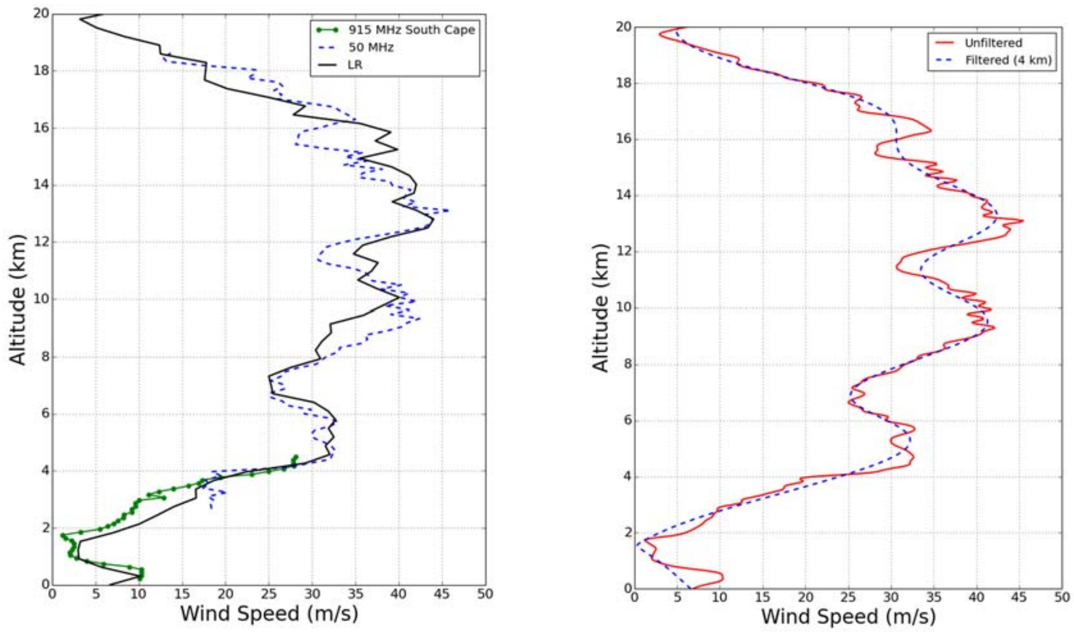
PrESTo contains a process to splice wind and thermodynamic profiles from multiple instruments to produce a single profile required for DOL launch vehicle assessments. Generating this wind profile utilizes benefits of both the LRFE and the DRWP by providing a wind profile that 1) contains measurements up to roughly 100 kft (30.5 km), making the profile suitable for input to vehicle steering commands and 2) can be updated frequently to produce the most up-to-date characterization of winds in altitude regions where launch vehicles are most sensitive to wind effects. This attribute of PrESTo advances the technology that the DOL community uses since no launch vehicle program has yet to implement such a process.

The algorithm used to splice profiles from multiple instruments consists of interpolating data from all instruments to defined altitudes, splicing profiles that overlap, and splicing the resultant profile with Earth-Global Reference Atmospheric Model (Earth-GRAM, Leslie and Justus 2010) input to create a profile up to 600 kft (183 km). Before implementing the splicing process, the algorithm interpolates all input wind component, temperature, pressure, and density profiles to a constant altitude interval and range to produce placeholders for all input profiles at identical altitudes. In addition, the algorithm flags excessively large gaps. The splicing process itself occurs near 6.6 kft (2 km) if DRWP data exist, near 60 kft (18 km) if DRWP or Jimsphere input data exist, and near 100 kft (30.5 km), which is the highest measurement altitude of the LRFE.

The algorithm generates a spliced wind profile using wind components from multiple sources, and then computes wind speed and wind direction from the spliced wind components' profiles. PrESTo can then use this wind profile to derive the spliced wind profile along any flight azimuth. The algorithm uses the LRFE and up to two additional instruments to generate a spliced wind component profile. These additional instruments could consist of any combination of 915-MHz DRWP, 50-MHz DRWP, and balloon profiles. Once the algorithm determines the instruments being used, it searches for overlap between profiles from different instruments. Figure 3 presents time concurrent LRFE, 915- and 50-MHz DRWP profiles and the resultant spliced profile. If two input profiles overlap, then the algorithm computes the spliced wind component within the overlapping region as the weighted average between the "low profile" and "high profile" (which denote the profiles that contains data below and above the overlap region, respectively). If no overlap exists, then the algorithm interpolates the wind component from the top of the 915-MHz DRWP profile to the wind component at the bottom of the 50-MHz DRWP profile. Interpolation only occurs in this case as balloon data exist at all altitudes that both DRWP systems measure.

Once the algorithm implements the splicing process on DRWP data, or Jimsphere data if only Jimsphere data are provided, the algorithm splices the resultant profile into the LRFE, then splices that resultant profile into the Earth-GRAM monthly mean profile. If the only input data consists of the LRFE profile, then the algorithm only splices the LRFE profile into the Earth-GRAM monthly mean profile. The algorithm produces spliced thermodynamic profiles using only the LRFE and Earth-GRAM input profiles as thermodynamic measurements are only provided by the LRFE.

The splicing algorithm contains an operation that performs a low-pass filter that attenuates wind components with spectral content below a constant wavelength. Generating a single wind profile from multiple measurement systems requires ensuring that all parts of the profile contain spectral content that all systems can resolve. Thus, a spliced wind profile must contain data only at wavelengths greater than the wavelength resolvable by the coarsest measurement system. Additionally, one might want to only characterize the wind profile that will persist through the launch countdown. Typically, steering commands utilize a wind profile filtered to a coarse wavelength (e.g., 4 km) that will persist over the several hours before launch. Subsequent wind profiles used to assess the steering command design occur closer to launch, and thus are filtered to a lesser extent to include those atmospheric features that will persist over shorter time periods. The algorithm implements a six-pole low-pass Butterworth filter on an individual wind component with 95% gain at the desired cutoff wavelength. The filtered plot in Figure 3 illustrates the effects of filtering as the profile filtered to a larger wavelength contains less small-scale atmospheric features. As launch approaches, the cutoff wavelength becomes smaller; yielding a filtered profile that contains smaller-scale features. The wind profile without any additional filtering represents the wind profile that all input systems



a) b)

Figure 3. Time correlated LRFE (1815 LST), 50- (1700 LST) and 915-MHz (1810 LST) DRWP profiles at the ER from 14 Jan. 2005 in a) and the resultant spliced and spliced & filtered profiles in b).

can resolve. Features that persist over time periods shorter than those that these instruments can resolve are accounted for statistically in vehicle design cycles. The algorithm does not filter thermodynamic profiles, as thermodynamic properties tend to persist over longer periods than winds persist. Upon completion of splicing and filtering, the user can have PrESTo write the atmospheric profile out to an ASCII formatted text file. This file can be provided to engineers for incorporation into DOL trajectory and loads evaluations.

5. CONCLUSION

PrESTo's splicing algorithm provides the capability to examine and generate a single profile of wind and thermodynamic parameters over the altitudes needed by the DOL community. The operation can generate wind profiles from multiple sources, and contains algorithms to realistically splice data from one source into data from another source. This software leverages off of the advantages from balloon- and DRWP-based measurement systems at the launch ranges for DOL operations. NASA's SLS is designing the vehicle and its DOL operations concept with the intention to use PrESTo software in support of vehicle DOL trajectory and loads evaluations.

6. REFERENCES

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